# Late Heavy Bombardment

<http://www.wisegeek.com/what-was-the-late-heavy-bombardment.htm>

The late heavy bombardment is a period of highly intensified asteroid impacts taking place between 3920 and 3850 million years ago (mya). Life itself was formed either a few dozen million years before the late heavy bombardment or near its conclusion.

Evidence for the late heavy bombardment was found by Apollo astronauts visiting the Moon. Out of all the rock samples they brought back, many of them clearly remelted after asteroid impacts, and these remelting events were clustered with ages 3920 million years or a hundred or so million years younger. This period of time thereafter became called the "lunar cataclysm." Asteroids from the Moon have been shown all to have the 3920 million year age limit, but they are not clustered around the short time thereafter, having ages ranging from 2500 to 3900 mya. By extension, it was inferred that Earth, Venus, and Mercury would have also experienced a substantial increase in asteroid impacts during this period.

If the late heavy bombardment really happened, then this is the damage that likely would have been done to Earth:

--22,000 or more impact craters with diameters of over 20 km

--about 40 impact basins with diameters of about 1000 km

--several impact basins with diameter of about 5,000 km

Serious environmental damage would have occurred every 100 years, making the planet a tough place to live, although early life did emerge during this time. Although the Earth had already cooled and solidified prior to this period, all elements of this geological era were erased, because the late heavy bombardment evidently destroyed most of the crust and therefore the oldest rocks to be dated have an age of 3850 million years. The period prior to that is known as the Hadean, after it, the Archean. The oldest bacterial fossils do not appear in the record until 3460 million years ago, but most who study early life believe that it originated several hundred million years before this.

<https://en.wikipedia.org/wiki/Late_Heavy_Bombardment>

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[](https://en.wikipedia.org/wiki/File:Lunar_cataclysm.jpg)

Artist's impression of the moon during the *Late Heavy Bombardment* (Lunar Cataclysm) and today

The **Late Heavy Bombardment** (abbreviated **LHB** and also known as the **lunar cataclysm**) is a hypothetical event thought to have occurred approximately 4.1 to 3.8 billion years ([Ga](https://en.wikipedia.org/wiki/Ga_(unit))) ago,[[1]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-taylor1-1) spanning the [Neohadean](https://en.wikipedia.org/wiki/Neohadean" \o "Neohadean) and [Eoarchean](https://en.wikipedia.org/wiki/Eoarchean" \o "Eoarchean) eras. During this interval, a disproportionately large number of asteroids apparently collided with the early [terrestrial planets](https://en.wikipedia.org/wiki/Terrestrial_planets) in the inner solar system, including [Mercury](https://en.wikipedia.org/wiki/Mercury_(planet)), [Venus](https://en.wikipedia.org/wiki/Venus), [Earth](https://en.wikipedia.org/wiki/Earth), and [Mars](https://en.wikipedia.org/wiki/Mars).[[2]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-2) The LHB happened after the Earth and other rocky planets had formed and [accreted](https://en.wikipedia.org/wiki/Accretion_(astrophysics)) [grow by accumulation] most of their mass, but still quite early in Earth history.

Evidence for the LHB derives from lunar samples brought back by the [Apollo](https://en.wikipedia.org/wiki/Apollo_program) astronauts. Isotopic dating of [Moon](https://en.wikipedia.org/wiki/Moon) rocks implies that most impact melts occurred in a rather narrow interval of time. Several hypotheses are now offered to explain the apparent spike in the flux of impactors (i.e., asteroids and comets) in the inner Solar System**, but no consensus yet exists**. The [Nice model](https://en.wikipedia.org/wiki/Nice_model) is popular among [planetary scientists](https://en.wikipedia.org/wiki/Planetary_science); it postulates that the [gas giant](https://en.wikipedia.org/wiki/Gas_giant) planets underwent [orbital migration](https://en.wikipedia.org/wiki/Planetary_migration) and scattered objects in the [asteroid](https://en.wikipedia.org/wiki/Asteroid_belt) and/or [Kuiper belts](https://en.wikipedia.org/wiki/Kuiper_belt) into eccentric orbits, and thereby into the path of the [terrestrial planets](https://en.wikipedia.org/wiki/Terrestrial_planet). Other researchers argue that the lunar sample data do not require a cataclysmic cratering event near 3.9 Ga, and that the apparent clustering of impact melt ages near this time is an artifact of sampling materials retrieved from a single large impact basin.[[1]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-taylor1-1) They also note that the rate of impact cratering could be significantly different between the outer and inner zones of the Solar System.[[3]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-3)

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## Evidence for a cataclysm[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=1" \o "Edit section: Evidence for a cataclysm)]

The main piece of evidence for a lunar cataclysm comes from the [radiometric ages](https://en.wikipedia.org/wiki/Radiometric_dating) of impact melt rocks that were collected during the Apollo missions. The majority of these impact melts are believed to have formed during the collision of asteroids or comets tens of kilometers across, forming impact craters hundreds of kilometers in diameter. The [Apollo 15](https://en.wikipedia.org/wiki/Apollo_15), [16](https://en.wikipedia.org/wiki/Apollo_16), and [17](https://en.wikipedia.org/wiki/Apollo_17) landing sites were chosen as a result of their proximity to the [Imbrium](https://en.wikipedia.org/wiki/Mare_Imbrium" \o "Mare Imbrium), [Nectaris](https://en.wikipedia.org/wiki/Mare_Nectaris" \o "Mare Nectaris), and [Serenitatis](https://en.wikipedia.org/wiki/Mare_Serenitatis) basins respectively.

Under study on Earth, the ages of impact melts collected at these sites clustered between about 3.8 and 4.1 Ga. The apparent clustering of ages of these was first noticed in the mid-1970s by Fouad Tera, Dimitri Papanastassiou, and Gerald Wasserburg who postulated that the ages record an intense bombardment of the Moon.[[4]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-4) They called it the "lunar cataclysm" and proposed that it represented a dramatic increase in the rate of bombardment of the Moon around 3.9 Ga. If these impact melts were derived from these three basins, then not only did these three prominent impact basins form within a short interval of time, but so did many others based on[stratigraphic](https://en.wikipedia.org/wiki/Stratigraphy) grounds. At the time, the conclusion was considered controversial.

As more data has become available, particularly from [lunar meteorites](https://en.wikipedia.org/wiki/Lunar_meteorites), this theory, while still controversial, has gained in popularity. The lunar meteorites are believed to randomly sample the lunar surface, and at least some of these should have originated from regions far from the Apollo landing sites. Many of the [feldspathic](https://en.wikipedia.org/wiki/Feldspar) lunar meteorites probably originated from the lunar far side, and impact melts within these have recently been dated. Consistent with the cataclysm hypothesis, none of their ages was found to be older than about 3.9 Ga.[[5]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-5) Nevertheless, the ages do not "cluster" at this date, but span between 2.5 and 3.9 Ga.[[6]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-6)

Dating of [howardite](https://en.wikipedia.org/wiki/Howardite" \o "Howardite), [eucrite](https://en.wikipedia.org/wiki/Eucrite" \o "Eucrite) and [diogenite](https://en.wikipedia.org/wiki/Diogenite" \o "Diogenite) (HED) meteorites and [H chondrite](https://en.wikipedia.org/wiki/H_chondrite) meteorites originating from the asteroid belt reveal numerous ages from 3.4–4.1 Ga and an earlier peak at 4.5 Ga. The 3.4–4.1 Ga ages has been interpreted as representing an increase in impact velocities as computer simulations using hydrocode reveal that the volume of impact melt increases 100–1000 times as the impact velocity increases from the current asteroid belt average of 5 km/s to 10 km/s. Impact velocities above 10 km/s require very high inclinations or the large eccentricities of asteroids on planet crossing orbits. Such objects are rare in the current asteroid belt but the population would be significantly increased by the sweeping of resonances due to giant planet migration.[[7]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-March_etal_2013-7)

Studies of the highland crater size distributions suggest that the same family of projectiles struck Mercury and the Moon during the *Late Heavy Bombardment*.[[8]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Strom_1979-8) If the history of decay of late heavy bombardment on Mercury also followed the history of late heavy bombardment on the Moon, the youngest large basin discovered, [Caloris](https://en.wikipedia.org/wiki/Caloris_basin" \o "Caloris basin), is comparable in age to the youngest large lunar basins, Orientale and Imbrium, and all of the plains units are older than 3 billion years.[[9]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-9)

## Criticisms of the cataclysm hypothesis[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=2" \o "Edit section: Criticisms of the cataclysm hypothesis)]

While the cataclysm hypothesis has recently gained in popularity, particularly among dynamicists who have identified possible causes for such a phenomenon, the cataclysm hypothesis is still controversial and based on debatable assumptions. Two criticisms are that (1) the "cluster" of impact ages could be an artifact of sampling a single basin's ejecta, and (2) that the lack of impact melt rocks older than about 4.1 Ga is related to all such samples having been pulverized, or their ages being reset.

The first criticism concerns the origin of the impact melt rocks that were sampled at the Apollo landing sites. While these impact melts have been commonly attributed to having been derived from the *closest basin*, it has been argued that a large portion of these might instead be derived from the Imbrium basin.[[10]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-10) The Imbrium impact basin is the youngest and largest of the multi-ring basins found on the central nearside of the Moon, and quantitative modeling shows that significant amounts of ejecta from this event should be present at all of the Apollo landing sites. According to this alternative hypothesis, the cluster of impact melt ages near 3.9 Ga simply reflects material being collected from a **single impact event**, Imbrium, and not several.

A second criticism concerns the **significance of the lack of impact melt rocks older than about 4.1 Ga**. One hypothesis for this observation that does not involve a cataclysm is that old melt rocks did exist, but that their ages have all been reset by the continuous effects of impact cratering over the past 4 billion years. Furthermore, it is possible that these putative samples could all have been pulverized to such small sizes that it is impossible to obtain age determinations using standard radiometric methods.[[11]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Hartmann_2003-11) Latest reinterpretation of crater statistics suggests that the flux on the Moon and on Mars may have been lower in general. Thus, the recorded crater population can be explained without any peak in the earliest bombardment of the inner solar system.

## Geological consequences on Earth[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=3" \o "Edit section: Geological consequences on Earth)]

If a cataclysmic cratering event truly occurred on the Moon, the Earth would have been affected as well. Extrapolating lunar cratering rates[[12]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment" \l "cite_note-12) to Earth at this time suggests that the following number of craters would have formed:[[13]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-13)

* 22,000 or more [impact craters](https://en.wikipedia.org/wiki/Impact_crater) with diameters >20 km (12 mi),
* about 40 [impact basins](https://en.wikipedia.org/wiki/Impact_basin) with diameters about 1,000 km (620 mi),
* several impact basins with diameters about 5,000 km (3,100 mi),

Serious environmental damage would occur about every 100 years, although [life](https://en.wikipedia.org/wiki/Life) is not known to have existed on Earth at this time.

Before the formulation of the LHB theory, geologists generally assumed that the Earth remained molten until about 3.8 Ga. This date could be found in all of the oldest known rocks from around the world, and appeared to represent a strong "cutoff point" beyond which older rocks could not be found. These dates remained fairly constant even across various dating methods, including the system considered the most accurate and least affected by environment, [uranium-lead dating](https://en.wikipedia.org/wiki/Uranium-lead_dating) of [zircons](https://en.wikipedia.org/wiki/Zircon). As no older rocks could be found, it was generally assumed that the Earth had remained molten until this date, which defined the boundary between the earlier [Hadean](https://en.wikipedia.org/wiki/Hadean) and later[Archean](https://en.wikipedia.org/wiki/Archean) eons.

Older rocks could be found, however, in the form of [asteroid](https://en.wikipedia.org/wiki/Asteroid) fragments that fall to Earth as [meteorites](https://en.wikipedia.org/wiki/Meteorites). Like the rocks on Earth, asteroids also show a strong cutoff point, at about 4.6 Ga, which is assumed to be the time when the first solids formed in the [protoplanetary disk](https://en.wikipedia.org/wiki/Protoplanetary_disk) around the then-young Sun. The Hadean, then, was the period of time between the formation of these early rocks in space, and the eventual solidification of the Earth's crust, some 700 million years later. This time would include the accretion of the planets from the disk and the slow cooling of the Earth into a solid body as the gravitational potential energy of accretion was released.

Later calculations showed that the rate of collapse and cooling depends on the size of the rocky body. Scaling this rate to an object of Earth mass suggested very rapid cooling, requiring only 100 million years.[[14]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-14) The difference between measurement and theory presented a conundrum at the time.

The LHB offers a potential explanation for this anomaly. Under this model, the rocks dating to 3.8 Ga solidified only after much of the crust was destroyed by the LHB. Collectively, the [Acasta Gneiss](https://en.wikipedia.org/wiki/Acasta_Gneiss" \o "Acasta Gneiss) in the North American cratonic shield and the gneisses within the [Jack Hills](https://en.wikipedia.org/wiki/Jack_Hills) portion of the Narryer Gneiss Terrane in Western Australia are the oldest continental fragments on Earth, yet they appear to post-date the LHB. The oldest mineral yet dated on Earth, a zircon from Jack Hills, predates this event, but it may simply be a fragment of crust left over from the LHB, contained within a much younger (~3800 Ma old) rock.[[*citation needed*](https://en.wikipedia.org/wiki/Wikipedia:Citation_needed)]

The Jack Hills zircon led to something of a revolution in our understanding of the Hadean eon.[[15]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-15) Older references generally show that Hadean Earth had a molten surface with prominent [volcanos](https://en.wikipedia.org/wiki/Volcano). The name "Hadean" itself refers to the "hellish" conditions assumed on Earth for the time, from the Greek [Hades](https://en.wikipedia.org/wiki/Hades). Zircon dating suggested, albeit controversially, that the Hadean surface was solid, temperate, and covered by acidic oceans. This picture derives from the presence of particular isotopic ratios that suggest the action of water-based chemistry at some time before the formation of the oldest rocks (see [Cool early Earth](https://en.wikipedia.org/wiki/Cool_early_Earth)).[[16]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-16)

Of particular interest, Manfred Schidlowski argued in 1979 that the carbon isotopic ratios of some sedimentary rocks found in [Greenland](https://en.wikipedia.org/wiki/Greenland) were a relic of organic matter. There was much debate over the precise dating of the rocks, with Schidlowski suggesting they were about 3800 Ma old, and others suggesting a more "modest" 3600 Ma. In either case it was a very short time for [abiogenesis](https://en.wikipedia.org/wiki/Abiogenesis) to have taken place, and if Schidlowski was correct, **arguably too short a time**. The *Late Heavy Bombardment* and the "re-melting" of the crust that it suggests provides a timeline under which this would be possible; [**life**](https://en.wikipedia.org/wiki/Life)**either formed immediately after the *Late Heavy Bombardment*, or more likely survived it**, having arisen earlier during the Hadean. Recent studies suggest that the rocks Schidlowski found are indeed from the older end of the possible age range at about 3850 Ma, suggesting the latter possibility is the most likely answer.[[17]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-AB-20021014-17) More recent studies have found no evidence for the isotopically light carbon ratios that were the basis for the original claims.[[18]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-18)[[19]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-19)[[20]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-20)

More recently, a similar study of Jack Hills rocks shows traces of the same sort of potential organic indicators. Thorsten Geisler of the Institute for Mineralogy at the [University of Münster](https://en.wikipedia.org/wiki/University_of_M%C3%BCnster) studied traces of carbon trapped in small pieces of diamond and graphite within zircons dating to 4250 Ma. The ratio of carbon-12 to carbon-13 was unusually high, normally a sign of "processing" by life.[[21]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-NS-20080702-21)

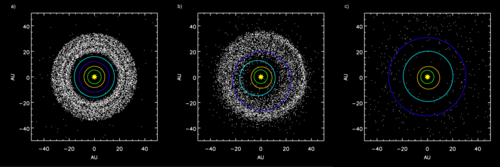
Three-dimensional computer models developed in May 2009 by a team at the [University of Colorado at Boulder](https://en.wikipedia.org/wiki/University_of_Colorado_at_Boulder) postulate that much of Earth's crust, and the microbes living in it, could have survived the bombardment. Their models suggest that **although the surface of the Earth would have been sterilized,**[**hydrothermal vents**](https://en.wikipedia.org/wiki/Hydrothermal_vents)**below the Earth's surface could have incubated life by providing a sanctuary for**[**heat-loving microbes**](https://en.wikipedia.org/wiki/Thermophile).[[22]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-RN-20090520-22)

In April 2014, scientists reported finding evidence of the largest terrestrial meteor [impact event](https://en.wikipedia.org/wiki/Impact_event) to date near the [Barberton Greenstone Belt](https://en.wikipedia.org/wiki/Barberton_Greenstone_Belt#Barberton_greenstone_belt). They estimated the impact occurred about 3.26 billion years ago and that the impactor was approximately 37 to 58 kilometers (23 to 36 miles) wide. The crater from this event, if it still exists, has not yet been found.[[23]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-23)

## Possible causes[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=4" \o "Edit section: Possible causes)]

### Gas giant migration[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=5" \o "Edit section: Gas giant migration)]

*For more details on this topic, see*[*Nice model*](https://en.wikipedia.org/wiki/Nice_model)*.*

[](https://en.wikipedia.org/wiki/File:Lhborbits.png)

Simulation showing outer planets and planetesimal belt: a) Early configuration, before Jupiter/Saturn reach 2:1 resonance b) Scattering of planetesimals into the inner Solar System after the orbital shift of Neptune (dark blue) and Uranus (light blue) c) After ejection of planetesimals by planets.[[24]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Gomes05-24)

A series of simulations by Gomes *et al.* start with a [Solar System](https://en.wikipedia.org/wiki/Solar_System) where the gas giant planets are in a tight orbital configuration.[[25]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-25) This configuration is in itself stable, but assuming a rich [trans-Neptunian belt](https://en.wikipedia.org/wiki/Trans-Neptunian_object), stray transneptunians interacted with these planets, causing them to migrate slowly during a time of several hundred million years. Jupiter is predicted to migrate inward, whereas the other planets go outwards. By this migration, the Solar System became catastrophically unstable when Jupiter and Saturn reached a 2:1 [orbital resonance](https://en.wikipedia.org/wiki/Orbital_resonance), causing the outer Solar System to reconfigure rapidly to a wide jovian system. As these planets migrated, resonances would be "swept" through the asteroid belt and Kuiper belt. These resonances would increase the [orbital eccentricity](https://en.wikipedia.org/wiki/Orbital_eccentricity) of the objects, allowing them to enter the inner Solar System and impact with the terrestrial planets.[[1]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-taylor1-1)

The Nice model has undergone some evolution since its initial publication. In recent works the giant planets begin in a multi-resonant configurations consistent with numerical models of the early Solar System.[[26]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Morbidelli_etal_2007-26) After the resonant configuration is destabilized by interactions with the trans-Neptunian belt[[27]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment" \l "cite_note-Levison_2011-27) a series of gravitational encounters occur. Among these are an encounter between one of the [ice giants](https://en.wikipedia.org/wiki/Ice_giant) and Saturn propelling the ice giant inward onto a Jupiter-crossing orbit followed by an encounter with Jupiter which drives the ice giant outward. Referred to as a [jumping-Jupiter scenario](https://en.wikipedia.org/wiki/Jumping-Jupiter_Scenario), these encounters quickly increase the separation between Jupiter and Saturn which has been found to be necessary to avoid excessively altering the eccentricity of the inner planets[[28]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Brasser_2009-28) and the inclination distribution of the asteroids.[[29]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Morbidelli_etal_2010-29) This scenario also significantly reduces the fraction of asteroids removed from the main asteroid belt leaving a now nearly depleted [inner band](https://en.wikipedia.org/wiki/E-belt_asteroids) of asteroids as the primary source of the impactors of the LHB.[[30]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Bottke-30) In numerical simulations the ice giant is often ejected following its encounter with Jupiter leading some to propose that the Solar System began with [five giant planets](https://en.wikipedia.org/wiki/Hypothetical_fifth_gas_giant).[[31]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Nesvorny_2011-31)

### Late Uranus/Neptune formation[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=6" \o "Edit section: Late Uranus/Neptune formation)]

According to one [planetesimal](https://en.wikipedia.org/wiki/Planetesimal" \o "Planetesimal) simulation of the establishment of the planetary system, the outermost planets Uranus and Neptune formed very slowly, over a period of several billion years.[[32]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-32) Harold Levison and his team have also suggested that the relatively low density of material in the outer Solar System during planet formation would have greatly slowed their accretion.[[33]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-33) This "late appearance" of these planets has therefore been suggested as a different reason for the LHB. However, recent calculations of gas-flows combined with planetesimal runaway growth in the outer Solar System imply that [Jovian planets](https://en.wikipedia.org/wiki/Jovian_planets) formed extremely rapidly, on the order of 10 My, which does not support this explanation for the LHB.

### Planet V hypothesis[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=7" \o "Edit section: Planet V hypothesis)]

*Main article:*[*Planet V*](https://en.wikipedia.org/wiki/Planet_V)

The Planet V hypothesis posits that a fifth terrestrial planet created the *Late Heavy Bombardment* when its meta-stable orbit entered the inner asteroid belt. The hypothetical fifth terrestrial planet, Planet V, had a mass less than half of Mars and originally orbited between Mars and the asteroid belt. Planet V's orbit became unstable due to perturbations from the other inner planets causing it to intersect the inner asteroid belt. After close encounters with Planet V many asteroids entered Earth-crossing orbits producing the *Late Heavy Bombardment*. Planet V was ultimately lost, likely plunging into the Sun. In numerical simulations an uneven distribution of asteroids, with the asteroids heavily concentrated toward the inner asteroid belt, has been shown to be necessary to produce the LHB via this mechanism.[[34]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Brasser_2011-34)

### Disruption of Mars-crossing asteroid[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=8" \o "Edit section: Disruption of Mars-crossing asteroid)]

A hypothesis proposed by Matija Ćuk posits that the last few basin-forming impacts were the result of the collisional disruption of a large Mars-crossing asteroid. This Vesta-sized asteroid was a remnant of a population which initially was much larger than the current main asteroid belt. Most of the pre-Imbrium impacts to these Mars-crossing objects with the early bombardment extending until 4.1 billion years ago. A lull in basin-forming impacts follows during which the lunar magnetic field decays. Roughly 3.9 billion years ago a catastrophic impact disrupts a Vesta-sized asteroid radically increasing the population of Mars-crossing objects. Many of these objects then evolve onto Earth-crossing orbits producing a spike in the lunar impact rate during which the last few lunar impact basins are formed. Cuk points to the weak or absent residual magnetism of the last few basins and a change in the size-frequency distribution of craters which formed during this late bombardment as evidence supporting this hypothesis.[[35]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_1012-35) The timing[[36]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_etal_2010-36)[[37]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Malhatra_2011-37)[[38]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_etal_2011-38)[[39]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Fasset_2012-39) and the cause[[40]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Marchi_2012-40) of the change in the size-frequency distribution of craters is controversial.

### Other potential sources[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=9" \o "Edit section: Other potential sources)]

A number of other possible sources of the *Late Heavy Bombardment* have been investigated. Among these are additional Earth satellites orbiting independently or as lunar Trojans, planetesimals left over from the formations of the terrestrial planets, Earth or Venus co-orbitals, and the breakup of a large main belt asteroid. Additional Earth satellites on independent orbits were shown to be quickly captured into resonances during the Moon's early tidally-driven orbital expansion and were lost or destroyed within in a few million years[[41]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_2008-41) Lunar Trojans were found to be destabilized within 100 million years by a solar resonance when the Moon reached 27 Earth radii.[[42]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_Gladman_2009-42)Planetesimals left-over from the formation of the terrestrial planets were shown to be depleted due to collisions and ejections too rapidly to form the last lunar basins.[[43]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Bottke_etal_2007-43) The long term stability of primordial Earth or Venus co-orbitals (Trojans or objects with horseshoe orbits) in conjunction with the lack of current observations indicate that they were unlikely to have been common enough to contribute to the LHB.[[44]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Cuk_etal_2012-44) Producing the LHB from the collisional disruption of a main belt asteroid was found to require at minimum a 1000 – 1500 km parent body with the most favorable initial conditions.[[45]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment#cite_note-Ito_Malhotra_2006-45)

## Exosystem with possible Late Heavy Bombardment[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=10" \o "Edit section: Exosystem with possible Late Heavy Bombardment)]

*Main article:*[*Eta Corvi*](https://en.wikipedia.org/wiki/Eta_Corvi)

Evidence[[46]](https://en.wikipedia.org/wiki/Late_Heavy_Bombardment" \l "cite_note-46) has been found for *Late Heavy Bombardment*-like conditions around the star [Eta Corvi](https://en.wikipedia.org/wiki/Eta_Corvi).

## See also[[edit](https://en.wikipedia.org/w/index.php?title=Late_Heavy_Bombardment&action=edit&section=11" \o "Edit section: See also)]

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| [Portal icon](https://en.wikipedia.org/wiki/File:Crab_Nebula.jpg) | [***Astronomy portal***](https://en.wikipedia.org/wiki/Portal:Astronomy) |
| [Portal icon](https://en.wikipedia.org/wiki/File:Earth-moon.jpg) | [***Space portal***](https://en.wikipedia.org/wiki/Portal:Space) |
| [Portal icon](https://en.wikipedia.org/wiki/File:Solar_system.jpg) | [***Solar System portal***](https://en.wikipedia.org/wiki/Portal:Solar_System) |

* [Cool Early Earth](https://en.wikipedia.org/wiki/Cool_Early_Earth)
* [Formation and evolution of the Solar System](https://en.wikipedia.org/wiki/Formation_and_evolution_of_the_Solar_System)

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# Shaped by collisions *Nature Geoscience more at pdf in RTB> Creation*

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**Melt rocks returned from the Moon date to a narrow interval of lunar bombardment about 4 billion years ago. There is now evidence to show that this so-called Late Heavy Bombardment spanned the entire Solar System.**

Several hundred million years after its formation, the inner Solar System was pummelled by impactors. Ages of melted rocks sampled during the Apollo missions cluster in time, indicating a bombardment of cataclysmic proportions that produced the Moon's oldest and largest impact basins. But with a limited data set, the hypothesized Late Heavy Bombardment was initially controversial. Today, evidence of a Late Heavy Bombardment has been identified on the Earth and the other terrestrial planets, the asteroid belt, the icy moons of the outer Solar System, and even the gas giants.

The Late Heavy Bombardment, it turns out, is a Solar System story. It is tempting to focus on the uniqueness of each planet — but the geosciences are rooted in a shared history with our planetary siblings. A web focus published with this issue (<http://go.nature.com/83PgXm>) explores how the shared history of large ancient impacts shaped the geologic evolution of the terrestrial planets and moons.

The earliest Solar System was a violent backdrop for planet formation. Following the Sun's birth, the planets grew through collisions out of gas and dusty debris that littered the primordial accretionary disk. The planetary embryos then continued to grow through collisions and mergers with each other. Giant impacts literally shook these protoplanets to their cores — the proto-Earth was probably hit by a Mars-sized body to form the Earth and Moon[1](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref1), and the anomalously smooth northern hemisphere of Mars could be explained as a giant impact basin[2](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref2). All this occurred relatively quickly, probably within 100 million years. As planet formation wound down and the Solar System became less cluttered, the cratering rates of large impactors should have declined to a trickle. But all was not serene.

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Instead, the Moon was pummelled, its largest impact basins, as dated from Apollo samples, indicating unexpectedly high cratering rates 600 million years after Solar System formation. Furthermore, the oldest known impact materials on Earth have been linked to the tail end of this violent interval[3](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref3). Volcanism and cratering on Mercury[4](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref4), geologic differences between Jupiter's icy moons[5](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref5), and a period of unusually high velocity collisions within the asteroid belt itself[6](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref6), have all been attributed to the Late Heavy Bombardment.

The geologic histories of planetary surfaces and the available samples of planetary materials point to a period of intense bombardment about 4 billion years ago. It is difficult to attribute such a late-occurring bombardment to the remnants of planetary accretion. The impactors of the Late Heavy Bombardment must then have been delivered to the inner Solar System from a different source.

Perhaps the most important collision for understanding the Late Heavy Bombardment was not between planetary bodies, but between planetary scientists. Historically, planetary geology and planetary orbital dynamics were two fields that seldom intersected, but, as discussed in a Progress Article on page [520](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1841.html), the quest to make sense of the anomalous period of the Late Heavy Bombardment has brought these disparate fields together. Numerical simulations suggest that the present-day orbital architecture of the outer Solar System can only be explained if the giant planets migrated after their formation into their present orbits, and that this migration occurred rapidly at about the same time as the Late Heavy Bombardment[7](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref7). Giant planet migration would have disturbed a portion of the asteroid belt, sending a pulse of asteroids on to planet-crossing orbits. If the simulations are correct, then the terrestrial planets can blame big brothers Jupiter and Saturn and their orbital growing pains for the thumping they received 4 billion years ago.

The details of the Late Heavy Bombardment, such as its duration and magnitude, are still open for debate (page [520](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1841.html)). Once a conundrum limited to the Moon, the Late Heavy Bombardment is now being tackled in studies that span the Solar System, as well as planetary science disciplines.

The shared violent history of ancient impacts of the Earth and its planetary siblings influenced the evolution of planetary surfaces, interiors and even atmospheres. Intriguingly, and perhaps not entirely by coincidence, life on Earth started towards the end of the Late Heavy Bombardment. Perhaps the building blocks of life were delivered by some of these ancient impacts. Perhaps heat delivered by impacts supported long-lasting and habitable hydrothermal systems in which life could have evolved. And after life took root on Earth, perhaps early biological material was ejected from Earth by impacts and transported to the Moon[8](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1885.html?WT.ec_id=NGEO-201307#ref8) or even, as the Commentary on page [510](http://www.nature.com/ngeo/journal/v6/n7/full/ngeo1866.html) explains, to a potentially habitable Mars. Thus life becomes a shared Solar System story as well.

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